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6. AUTHOR(S)
B. H. Tyrone*, A. J. Seltzer*+, and A. B. Buckman*

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
AFIT Student Attending:
Austin Texas Univ.

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Reduced Minimum Detectable Phase Shift in a Fiber Optic Sensor with Electro-optic Feedback

B. H. Tyrone *, A.J. Seltzer *+, and A. B. Buckman*+

*Electrical and Computer Engineering Department, University of Texas, Austin 78712
and
+Research Applications, Inc., Austin TX. 78701

This letter reports a reduced minimum detectable phase shift obtained with a fiber interferometric sensor incorporating both common-mode compensation and electro-optic feedback to enhance measurand sensitivity. Experimental results using a tracking approach to signal-processing have resulted in a minimum detectable phase shift of 0.2 μradians/$\sqrt{(Hz)}$, over two orders of magnitude lower than results with a conventional Mach-Zehnder optical circuit with the same signal-processing electronics and over one order of magnitude lower than the 5 μradians/$\sqrt{(Hz)}$ level which represents current state-of-the-art.

Fiber interferometers measure small path length changes in an optical fiber which result from a variety of different measurands [1], including temperature, pressure, accelleration, displacement, electric and magnetic fields and chemical concentrations. The most successful approaches have utilized a conventional Mach-Zehnder Interferometer (MZI) and sophisticated signal processing to extract the measurand from the transmittance of the interferometer.

The extreme sensitivity of optical phase shifts in fibers to many environmental variables causes drifts in these quantities to be mistaken for a change in the measurand. In order to reduce the effects of common-mode noise in a standard MZI, the two path lengths must be as nearly equal as possible. With careful fabrication, these lengths can be within approximately 1mm of each other. This path difference is thousands of optical wavelengths, and still allows much of the common-mode noise to appear as a transmittance change at the interferometer output.

In earlier work, we analyzed and demonstrated an enhanced, common-mode compensated fiber interferometer [2-4] with two new features: 1) one additional pair of optical paths gives rise to two points along the transmittance vs. phase curve which are independent of small environmental perturbations common to all paths within the circuit (common-mode compensation); and 2) electro-optic feedback (EOF) distorts the transmittance vs. phase curve, creating narrow regions of greatly enhanced sensitivity to small phase shifts in a selected optical path [3,4].

Reference [3] demonstrated this interferometer in a free running mode, showing the coincidence of enhanced sensitivity and common-mode compensation at the same phase bias. This Letter reports measured minimum detectable phase shifts for this interferometer operated with a *modified phase-tracking* control system which maintains phase biases in both path pairs at the designed operating point.

The optical circuit and electronic signal processing is shown schematically in Fig. 1. Couplers C1, C2, and C3 are single-mode evanescent 3dB couplers, while the power division ratio of C4 is chosen such that only a very small fraction of the power incident in path r is coupled to the detector as the control signal, X(t). Under these conditions, the transmittance of our interferometer (referred to as a 1.5 MZI due to its resemblance to one and a half Mach-Zehnders placed in series) is obtained numerically from the solution of the transcendental equation [3],

$$T = \frac{1}{2}\left[\, 1 \pm \sin\phi \sin(P + kT)\right] \tag{1}$$

where k is the electro-optic feedback gain coefficient, and the loop phase shifts are defined by

$$\phi = \frac{2\pi n_{eff}}{\lambda}\left[\, L_2 - L_1\right] \tag{2}$$

$$P = \frac{2\pi n_{eff}}{\lambda}\left[\, L_s - L_r\right] \tag{3}$$

The sign in (1) is determined by which output is used. The phase, ϕ, controls the fringe visibility, and small phase shifts in P about the bias point are to be measured [1-3]. The optical path lengths,

L_j, in (2-3) are those of paths 1, 2, s, and r in Fig. 1, and n_{eff} is the effective index of the single-mode fiber at the operating wavelength, λ.

In order to implement a phase-tracking approach to signal processing in this interferometer, both phase shifts, ϕ and P must be controlled at preset values with feedback loops. The system in Fig.1 accomplishes this by imposing a "psuedo-common-mode dither" on the interferometer. This dither signal can be generated by modulating the laser wavelength, or as in this experiment, by supplying two small sinusoidal voltages of amplitudes D_1 and D_o, at the dither frequency $\omega_d/2\pi$ to the piezos which control ϕ and P. If the ratio of these two amplitudes obeys the relation,

$$\frac{D_0}{D_1} = \frac{L_s - L_r}{L_2 - L_1} \tag{4}$$

then the resulting perturbation affects the transmittance in the same way as a common mode perturbation. Thus, when the phase biases and electro-optic feedback parameter are set for common-mode compensation, the dither component in T(t) vanishes. To set the ratio of amplitudes in (4), only the ratio of the length differences needs to be accurately known. Since the path lengths themselves are macroscopic distances, this ratio can be determined very accurately. Figure 2 shows a numerical simulation of the quasi-dc and dither frequency components of X and T for $k = 3$. Since the component of T(t) at the dither frequency, $T(\omega_d)$, passes through zero at the value of P corresponding to the common-mode compensation point, $T(\omega_d)$ changes phase by π radians as P passes throught that point. However, $X(\omega_d)$ passes through zero and reverses phase at the extrema in X, since X is just proportional to the output of a conventional Mach-Zehnder interferometer.

Logic unit B in Fig.1. controls ϕ by comparing the quasi-dc value of X and the phase of $X(\omega_d)$ to their values at the designed phase bias for ϕ. The inputs to this logic unit are X and $X(\omega_d)$, filtered out of X(t) by the filter. The output of Logic unit B is a correction signal to the piezo which adjusts ϕ. Logic unit A controls P for phase tracking in a similar manner, using $T(\omega_d)$ and T filtered from T(t).

The purpose of this sensor is to demonstrate a very low minimum detectable phase shift, rather than to track larger phase shifts over a very wide dynamic range. Therefore, for this experiment, the time constants in the electronic feedback loops controlling ϕ and P are set much longer than that of the EOF amplifier loop which enhances the interferometer sensitivity. Slow changes in P appear at the electrical output, $P_b(t)$ at the right of Fig. 1, while more rapid changes appear at the detector output T(t).

The system described above was implemented with wirewrapped electronics, utilizing readily available electronic components. The dither frequency for this system was 10.5 KHz, and a calibration signal equivalent to 125 μradians at 16.5 KHz was applied to path s. In order to determine the minimum detectable measurand, defined as the phase shift just visible above the background noise, a power spectrum analyzer was utilized to determine the power of the output T(t) as a function of frequency. Power spectra obtained are shown in Figure 3, indicating the 1/f noise, the oscillations around the preset phase bias, and the measurand. When the power of the input phase shift signal is equal to the noise (i.e. the signal to noise ratio is unity), that phase shift

equals the minimum detectable measurand, at that frequency. No extraordinary measures were taken to minimize the environmental or electronic noise, so these results are typical of wire-wrapped, poorly shielded electronics, and fiber optics in closed but not evacuated containers, in a laboratory setting.

The performance of this design can be compared with that of others in two ways. The first comparison simply considers the lowest minimum detectable phase shift. This system demonstrated a minimum detectable phase shift of 200 nradians/$\sqrt{Hz}$, over an order of magnitude lower than the previous best values reported [5-7]. This absolute comparison, however striking, actually understates the potential of this approach. A second experiment, with the light introduced at coupler C2 instead of C1 and the feedback parameter k set to zero in Fig. 1, converts the system into a conventional Mach-Zehnder sensor operated with exactly the same electronics as the enhanced one. The measured minimum detectable phase shift for this conventional configuration was 50 μradians/$\sqrt{Hz}$. Therefore, the enhanced optical circuit lowered the minimum detectable phase shift by a factor of over 100, compared to an *equivalent* conventional interferometer. More careful electronic assembly, and mechanical shielding of the interferometer should take the performance of our conventional sensor to around the 5 μradians/$\sqrt{Hz}$ level reported by others for conventional fiber optic interferometers. It seems reasonable to expect that the same measures would lead to a 20 nradians/$\sqrt{Hz}$ minimum detectable phase shift for the enhanced sensor with electro-optic feedback.

Figure 3 shows the power spectral output of the interferometer with and without electrooptic feedback, showing the 50dB increase in signal response, without an increase in the system noise. In order to verify the source of the noise, and to see if improved electronics assembly would reduce the minimum detectable value significantly, the power spectrum of the interferometer was taken without the tracking system active (the operation position was set manually). The noise floor was about 5dB lower than that in Fig.3, which supports the conclusion that the system noise is dominated by the tracking electronics , and that further reduced minimum detectable phase shifts can be expected with a more careful optimization.

In conclusion, we have demonstrated a reduced minimum detectable phase shift in a novel fiber optic sensor circuit incorporating sensitivity enhancement by electro-optic feedback and common-mode compensation, controlled using phase-tracking electronics. The resulting minimum detectable phase shift is over an order of magnitude lower than the best previously reported results, and reduction by another order of magnitude appears feasible with improvements in the electronics.

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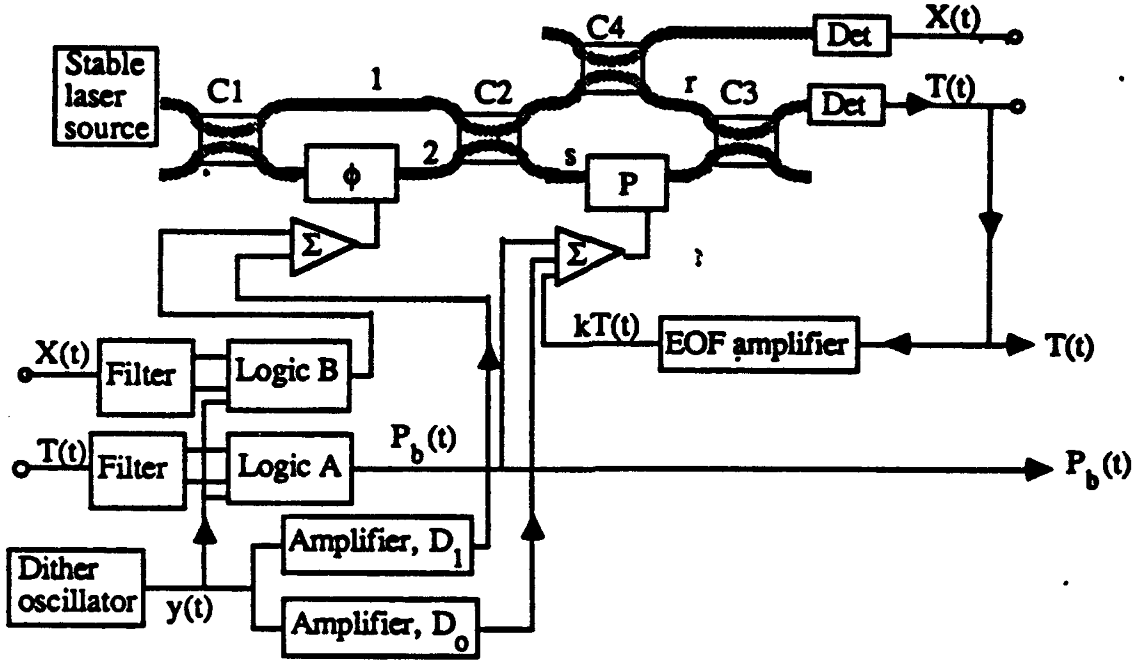


Figure 1: Optical and electrical schematic of enhanced fiber optic sensor with control system.

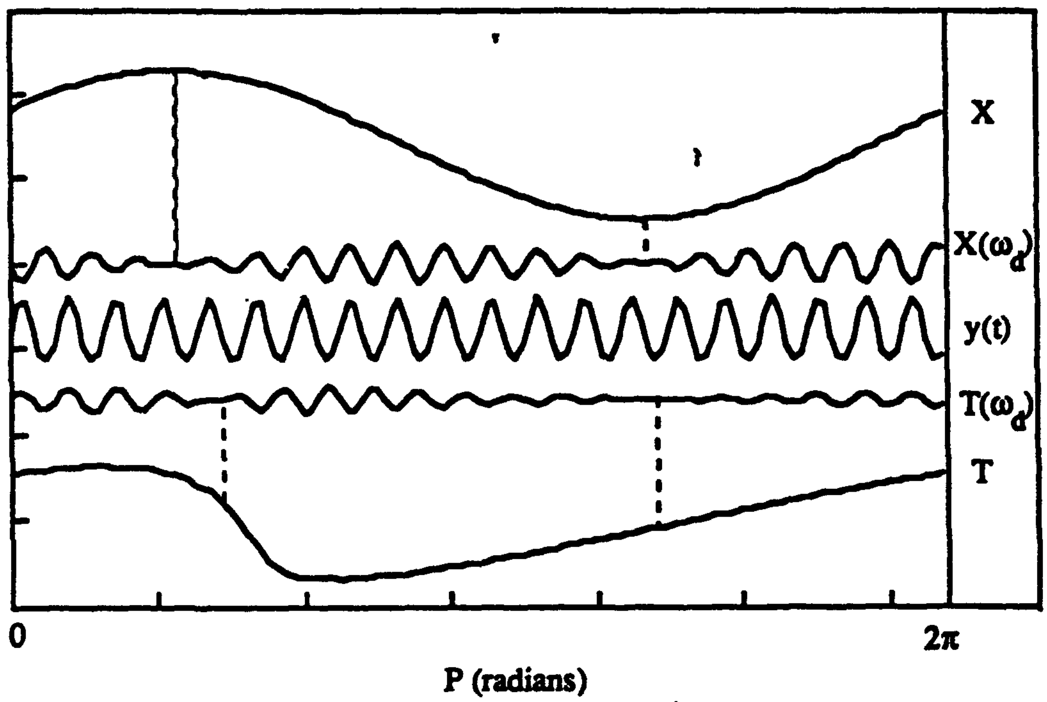
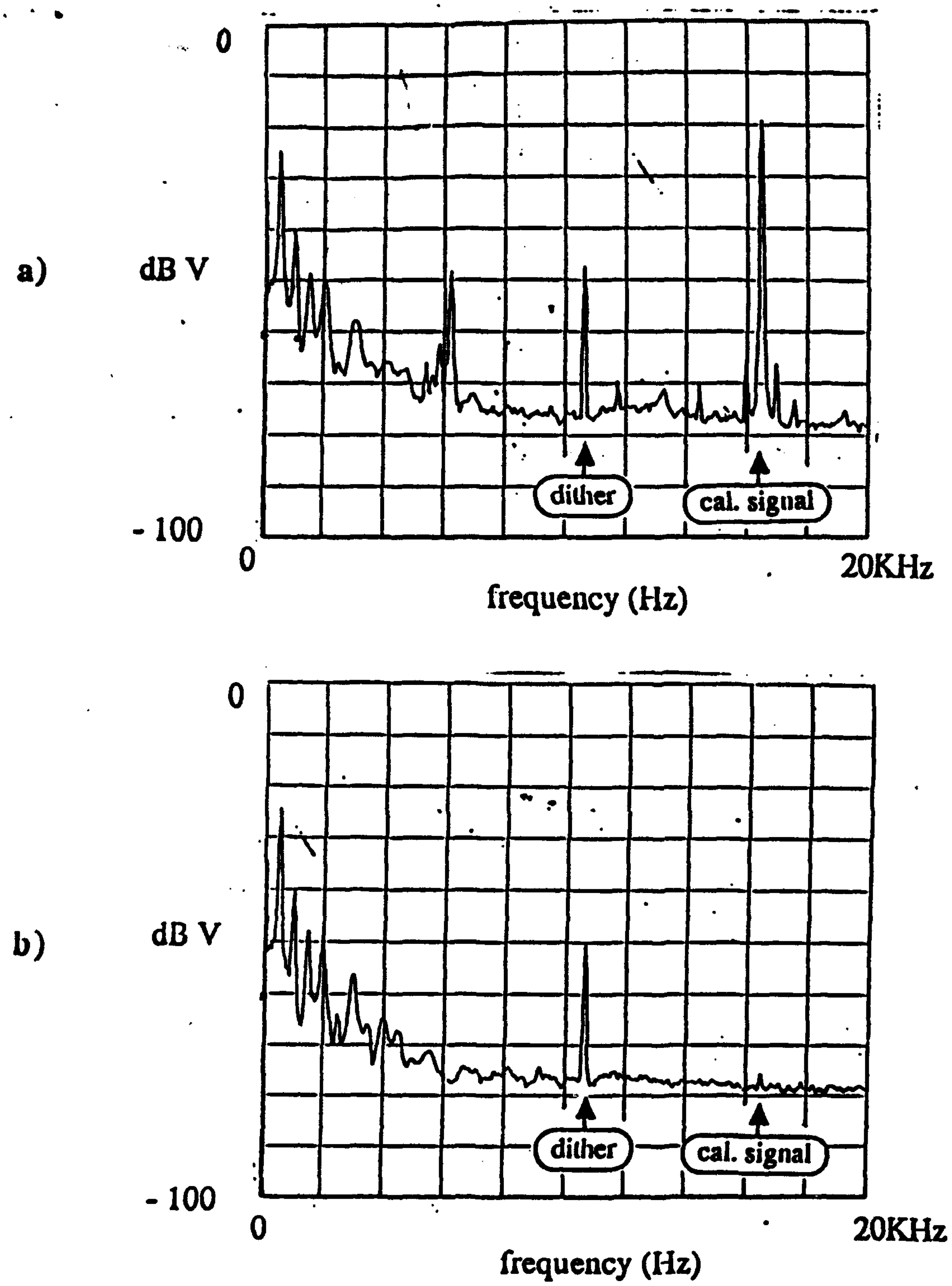


Figure 2. Signal components from Fig.1 over one cycle of the phase shift, P, for k = 3.



ıre 3. Measured output spectra with calibration signal at 16.5 KHz applied to the phase-shifter, P, in Fig. 1: a) enhanced sensor of Fig.1; and b) equivalent conventional interferometer.